Test of unparticle long range forces from perihelion precession of Mercury

Suratna Das , Subhendra Mohanty and Kumar Rao

Physical Research Laboratory, Ahmedabad 380009, India.

Abstract

Unparticle exchange gives rise to long range forces which deviate from the inverse square law due to non-canonical dimension of unparticles. It is well known that a potential of the form r^{-n} where n is not equal to one gives rise to a precession in the perihelion of planetary orbits. We calculate the constraints on unparticle couplings with baryons and leptons from the observations of perihelion advance of Mercury orbit.

PACS : 98.80.Cq, 11.15.Tk, 11.25.Hf

Recently a new class of particles with dimensions different from their canonical scaling dimensions have been proposed to exist in the effective low energy theory [1]. One assumes that an ultraviolet theory has a IR fixed point at some scale Λ_u where the fields become conformal invariant. The effective coupling of the ultraviolet theory operators O_{UV} of dimension d_{uv} with the standard model operators O_{SM} of dimension n are suppressed by a heavy mass scale M_u and can be written as

$$\frac{1}{M_u^{d_{uv}+n-4}}\,O_{UV}O_{SM}, \tag{1}$$

where d_{uv} is the canonical dimension of the operator O_{UV}. Below the scale Λ_u (conventionally assumed as 1 TeV), the fields of the UV theory become scale invariant and by dimensional transmutation acquire a dimension d_u which is different from their canonical dimension. These conformally coupled unparticle operators O_U will couple to the standard model operators as

$$\left(\frac{\Lambda_u}{M_u}\right)^{d_{uv}+n-4}\frac{1}{\Lambda_u^{d_u+n-4}}\,O_U\,O_{SM}. \tag{2}$$

It has been pointed out [2] that the exchange of scalar (pseudoscalar) unparticles can give rise to spin independent (spin-dependent) long range forces. Long range forces from vectors and axial-vectors have been studied in [2, 4]. Tensor unparticles can couple to the energy momentum tensor and mimic gravity as pointed out in [3]. Unparticle exchange gives rise to long range forces which deviate from the usual inverse square law for massless particles due to the anomalous scaling of the unparticle propagator. In [3, 4] bounds have been put on the unparticle couplings from long range force experiments [5].

It is well known that a deviation from the Newtonian inverse square gravity will result in unclosed orbits which results in a shift in perihelion of planetary orbits. Since exchange of massless unparticles gives rise to long range forces which deviate from the inverse square law we expect an additional contribution to the perihelion shift of planets in addition to that caused by general relativity. In this paper we consider the effect on the perihelion shift of Mercury due to the coupling of tensor and vector unparticles to SM particles. The perihelion shift due to general relativistic effects has been measured to 0.3% level and thus provides tight constraints on additional long range forces [6]. We find that this gives more stringent bounds on unparticle couplings compared to the one from fifth force search experiments at solar system distances [5].

Some consequences of unparticles in astrophysical phenomena has been explored in [10, 11, 12, 13]. There has also been a large amount of work on the theory and phenomenology of unparticles [14].

UNGRAVITY FROM TENSOR UNPARTICLES

We take the gravitational coupling of the tensor unparticle (ungravitons [3]) to the stress-energy tensor $T_{\mu\nu}$ to be of the form

$$\kappa_* \frac{1}{\Lambda_u^{d_u-1}} \sqrt{g} T^{\mu\nu} O^U_{\mu\nu}, \tag{3}$$

where $\kappa_* = \frac{1}{\Lambda_u}\left(\frac{\Lambda_u}{M_u}\right)^{d_{uv}}$. We impose the gauge symmetry as in the case of gravity,

$$\begin{aligned} x_\mu &\rightarrow x_\mu + \epsilon_\mu & (4)\\ O^U_{\mu\nu} &\rightarrow O^U_{\mu\nu} + \frac{\Lambda_u^{d_u-1}}{\kappa_*}\left(\partial_\mu \epsilon_\nu + \partial_\nu \epsilon_\mu\right), & (5) \end{aligned}$$

which ensures that the ungraviton remains massless below the scale Λ_u. The massless ungraviton results in long range forces which can be probed at solar system length scales.

The ungraviton propagators are [3]

$$\Delta^{\mu\nu\alpha\beta}(P) = B_{d_u} P^{\mu\nu\alpha\beta}(-P^2)^{d_u-2}, \tag{6}$$

where the normalization factor B_{d_u} is

$$B_{d_u} \equiv -\left(\frac{8\pi^{\frac{3}{2}}}{(2\pi)^{2d_u}}\right) \frac{\Gamma\left(2-d_u\right)\Gamma\left(d_u+\frac{1}{2}\right)}{\Gamma\left(2d_u\right)}, \tag{7}$$

and $P^{\mu\nu\alpha\beta}$ is the projection operator of the form

$$P^{\mu\nu\alpha\beta}(P) \equiv \frac{1}{2}(P^{\mu\alpha}P^{\nu\beta} + P^{\mu\beta}P^{\nu\alpha} - \alpha P^{\mu\nu}P^{\alpha\beta}), \tag{8}$$

where $P^{\mu\nu} = \left(-\eta^{\mu\nu} + \frac{P^\mu P^\nu}{P^2}\right)$. For massless ungravitons, obeying the gauge condition of Eq (5), $\alpha = 1$.

The ungravitational potential is obtained by taking the Fourier transform of the propagator $\Delta^{\mu\nu\alpha\beta}$ in the static limit $(P^0 = 0)$:

$$V_u(r) = \frac{\kappa_*^2}{\Lambda_u^{2d_u-2}} \int \frac{d^3\mathbf{P}}{(2\pi)^3} T_{\mu\nu}\Delta^{\mu\nu\alpha\beta}(P^0=0) T_{\alpha\beta} e^{i\mathbf{P}\cdot\mathbf{x}}, \tag{9}$$

where $|\mathbf{x}| = r$. Evaluating the integral gives

$$\begin{aligned} V_u(r) &= -m_1 m_2 \left(\frac{\kappa_*^2}{\Lambda_u^{2d_u-2}}\right)\left(\frac{2}{\pi^{2d_u-1}}\right)\frac{\Gamma\left(d_u+\frac{1}{2}\right)\Gamma\left(d_u-\frac{1}{2}\right)}{\Gamma\left(2d_u\right)}\left(\frac{1}{r^{2d_u-1}}\right) \\ &= -\frac{G_u m_1 m_2}{r^{2d_u-1}}, \end{aligned} \tag{10}$$

where G_u is defined to be

$$G_u \equiv \frac{\kappa_*^2}{\Lambda_u^{2d_u-2}} C(d_u), \tag{11}$$

and $C(d_u)$ is

$$C(d_u) \equiv \left(\frac{2}{\pi^{2d_u-1}}\right)\frac{\Gamma\left(d_u+\frac{1}{2}\right)\Gamma\left(d_u-\frac{1}{2}\right)}{\Gamma\left(2d_u\right)}. \tag{12}$$

We notice that if the anomalous dimension (d_u) of $O_{\mu\nu}$ is not equal to 1 there are deviations from the inverse square law. So for $d_u \neq 1$ the total potential will be of the form :

$$\begin{aligned} V(r) &= -\frac{G m_1 m_2}{r} - \frac{G_u m_1 m_2}{r^{2d_u-1}}. \\ &= -\frac{G m_1 m_2}{r}\left[1 + \frac{1}{G\Lambda_u^2}\left(\frac{\Lambda_u}{M_u}\right)^{2d_{uv}}\frac{C(d_u)}{\Lambda_u^{2d_u-2}}\frac{1}{r^{2d_u-2}}\right]. \end{aligned} \tag{13}$$

We will consider the case $d_u > 1$ as $d_u < 1$ will lead to forces which fall off slower than gravity and can be easily ruled out from fifth force experiments [5].

Perihelion precession of mercury orbit

In polar co-ordinates (r, θ), the equation of motion of a planet's orbit around the Sun is

$$\ddot{r} - r\dot{\theta}^2 + \frac{V'(r)}{m_p} = 0, \tag{14}$$

where m_p is the mass of the planet and $\dot{}$ and $'$ represent derivatives with respect to time t and distance r respectively. The angular momentum of the planet $l = m_p r^2 \dot{\theta}$ is a constant of motion.

Changing variables to $u(\theta) = \frac{1}{r(\theta)}$, Eq (14) can be written as

$$u'' + u = \alpha + \beta u^{2d_u-2}. \tag{15}$$

Here $'$ represents derivative with respect to θ and $\alpha \equiv \frac{M m_p^2 G}{l^2}$ and $\beta \equiv \frac{M m_p^2 G_u (2d_u-1)}{l^2}$, where M is the mass of the Sun. This is an inhomogeneous second order ordinary differential equation. Assuming the deviation from the inverse square law to be very small, we have

$\beta << \alpha$. So Eq (15) can be solved using a perturbation expantion in β. To first order in β we assume the form of the solution to be

$$u(\theta) = u_0(\theta) + \beta u_1(\theta), \tag{16}$$

where u_0 is the solution of the ODE

$$u_0'' + u_0 = \alpha, \tag{17}$$

and u_1 is the particular solution of the inhomogeneous equation

$$u_1'' + u_1 = u_0^{2d_u - 2}. \tag{18}$$

The solution of Eq (17) is

$$u_0 = \frac{1 - e\cos(\theta)}{a(1 - e^2)}, \tag{19}$$

where a is the semi-major axis of the elliptical orbit of the planet, given by

$$a = \frac{l^2}{M m_p^2 G(1 - e^2)} \tag{20}$$

and e is the eccentricity of the orbit. As the eccentricity of Mercury's orbit is very small we keep terms only upto $\mathcal{O}(e)$ and neglect the higher order terms in Eq (19). Using the above form of u_0, $u_1(\theta)$ obeys the equation

$$u_1'' + u_1 = \frac{1}{a^{2d_u - 2}} - \frac{(2d_u - 2)\, e\cos(\theta)}{a^{2d_u - 2}}. \tag{21}$$

This has the particular solution

$$u_1 = \frac{1}{a^{2d_u - 2}} - \frac{(d_u - 1)\, e}{a^{2d_u - 2}}\theta\sin(\theta). \tag{22}$$

Thus, from Eq (16), the trajectory of the planet to order β is given by

$$u = \frac{1}{a} + \beta\frac{1}{a^{2d_u - 2}} - \frac{e}{a}\left[\cos(\theta) + \frac{\beta\,(d_u - 1)}{a^{2d_u - 3}}\theta\sin(\theta)\right]. \tag{23}$$

For small β, Eq (23) can be written as

$$u \approx \frac{1}{a} + \beta\frac{1}{a^{2d_u - 2}} - \frac{e}{a}\left[\cos\left(\theta - \frac{\beta\,(d_u - 1)}{a^{2d_u - 3}}\theta\right)\right]. \tag{24}$$

For one complete rotation with a perihelion shift the condition is

$$\theta\left(1 - \frac{\beta\,(d_u - 1)}{a^{2d_u - 3}}\right) = 2\pi, \tag{25}$$

which gives

$$\theta \approx 2\pi \left(1 + \frac{\beta\,(d_u - 1)}{a^{2d_u - 3}}\right), \tag{26}$$

keeping only terms linear in β. So the perihelion shift induced by ungraviton couplings is given by

$$\begin{aligned} \delta\theta &= 2\pi \left(\frac{\beta\,(d_u - 1)}{a^{2d_u - 3}}\right) \\ &= (d_u - 1)(2d_u - 1)C(d_u)\frac{2\pi}{G\Lambda_u^2}\left(\frac{\Lambda_u}{M_u}\right)^{2d_{uv}} \frac{1}{\Lambda_u^{2d_u - 2}}\frac{1}{a^{2d_u - 2}}. \end{aligned} \tag{27}$$

As expected, the perihelion shift vanishes for $d_u = 1$, as it should since it corresponds to the usual inverse square law case (with a different gravitational constant). Comparing the expression for the unparticle potential Eq (13) (for $r = a$) with the expression for perihelion advance we see that they are related as

$$\delta\theta \simeq (d_u - 1)(2d_u - 1)2\pi\frac{V_u}{V_N}, \tag{28}$$

where V_u is the unparticle exchange potential and V_N is the Newtonian potential. The constraint on the ungravity couplings derived from mercury perihelion are more stringent than that from fifth force measurement by testing deviation from Kepler's Law at planetary distances [7],[8]. However at milimeter scales there are stringent tests of deviations of Newton's Law as has been noted in [3],[4].

The observed precession of perihelion of mercury is 43.13 ± 0.14 arcsec/century [9] and the prediction from general relativity is 42.98 arcsec/century. This means that at 2-σ the unparticle contribution is $-0.13 < \delta\theta < 0.43$. We derive a limit on unparticle coupling by demanding that the unparticle contribution does not exceed the discrepency between measurement and GR. From the 2-σ upper bound on the possible contribution from unparticle given by Eq (28) we get the limit

$$(d_u - 1)(2d_u - 1)C(d_u)\frac{2\pi}{G\Lambda_u^2}\left(\frac{\Lambda_u}{M_u}\right)^{2d_{uv}} \frac{1}{(a\Lambda_u)^{2d_u - 2}}\left(\frac{\text{century}}{T}\right) < 0.43 \text{ arcsec} \tag{29}$$

per century, where $T = 87.96$ days is the orbital time period of Mercury.

In Fig (1) we plot $\log\left(\frac{M_u}{\text{GeV}}\right)$ vs d_u which gives the tensor unparticle contribution of 0.43 arcsec/century to the perihelion advance of mercury. We have taken $d_{uv} = 1$ and the values of Λ_u from 1 TeV to 1000 TeV. The areas above the curves represent the allowed regions for M_u and d_u at 2-σ for different values of Λ_u .

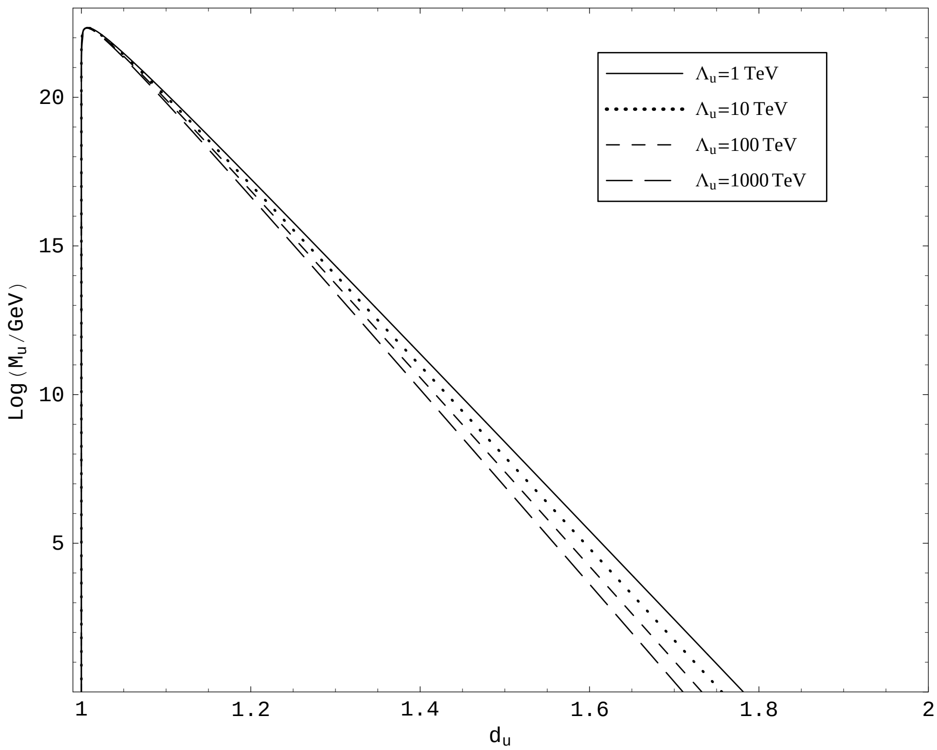

FIG. 1: Regions above the curves represent the allowed values of $\log\left(\frac{M_u}{\text{GeV}}\right)$ and d_u from observations of Mercury orbit.

LONG RANGE FORCE FROM VECTOR UNPARTICLES

Now we consider long range forces resulting from the coupling of vector unparticles [2, 4] to baryonic and leptonic currents. The effective coupling is of the form

$$\frac{\lambda}{\Lambda_u^{d_u-1}} J^\mu O_\mu^U, \tag{30}$$

where J_μ is the baryonic or leptonic current. As in the tensor case, we assume that the unparticle operator O^U and the fermion fields Ψ obey a gauge symmetry

$$\begin{aligned} \Psi &\rightarrow \exp[i\alpha]\Psi \\ O_\mu^U &\rightarrow O_\mu^U + \frac{\Lambda_u^{d_u-1}}{\lambda}\partial_\mu \alpha. \end{aligned} \tag{31}$$

As a result of this $U(1)$ gauge symmetry the vector unparticle remains massless below the scale Λ_u. The gauge unparticle propagator is

$$\Delta^{\mu\nu} = A_{d_u} P^{\mu\nu} (-p^2)^{d_u-2}, \tag{32}$$

where

$$A_{d_u} \equiv \frac{16\pi^{\frac{5}{2}}}{(2\pi)^{2d_u}} \frac{\Gamma\left(d_u + \frac{1}{2}\right)}{\Gamma\left(d_u - 1\right)\Gamma\left(2d_u\right)}, \tag{33}$$

and

$$P^{\mu\nu}(p) = \eta^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}. \tag{34}$$

As usual, we get the unparticle exchange potential by taking the Fourier transform of the propagator given in Eq (32) in the static limit. This gives

$$\begin{aligned} V_u(r) &= \frac{1}{2\pi^{2d_u}} \frac{\lambda^2}{\Lambda_u^{2d_u-2}} \frac{\Gamma\left(d_u + \frac{1}{2}\right)\Gamma\left(d_u - \frac{1}{2}\right)}{\Gamma\left(2d_u\right)} \frac{N_1 N_2}{r^{2d_u-1}} \\ &= \frac{C'\left(d_u\right)\lambda^2 N_1 N_2}{r^{2d_u-1}}, \end{aligned} \tag{35}$$

where

$$C'(d_u) \equiv \frac{1}{2\pi^{2d_u}} \frac{1}{\Lambda_u^{2d_u-2}} \frac{\Gamma\left(d_u + \frac{1}{2}\right)\Gamma\left(d_u - \frac{1}{2}\right)}{\Gamma\left(2d_u\right)}, \tag{36}$$

is a constant and N_1 and N_2 are the total number of baryons ($N_i = \frac{M_i}{m_n}$,where M_i is the mass of the sun or the planet and m_n is the nucleon mass) in the Sun and the planet. Hence the total potential is

$$\begin{aligned} V(r) &= V_N(r) + V_u(r) \\ &= -\frac{Gm_1 m_2}{r}\left[1 - \frac{C'\left(d_u\right)\lambda^2 N_1 N_2}{Gm_1 m_2} \frac{1}{r^{2d_u-2}}\right]. \end{aligned} \tag{37}$$

By following the same methodology as in the tensor case we find the perihelion shift to be

$$\delta\theta = -2\pi(d_u - 1)(2d_u - 1)\frac{C'\left(d_u\right)\lambda^2 N_1 N_2}{Gm_1 m_2} \frac{1}{a^{2d_u-2}}. \tag{38}$$

Vector unparticle exchange would cause a retardation in the perihelion of mercury orbit ($\delta\theta < 0$) due to the fact that the force is repulsive. At 1-σ the discrepancy between theory and experiment is still positive ($0.01 < \delta\theta < 0.29$) which means that the vector unparticle force can be ruled out at 1-σ. At $2-\sigma$ the allowed range for a unparticle vector contribution is $-0.13 < \delta\theta < 0.43$. The maximum value of this retardation allowed from observations [9] and the prediction of general relativity is 0.13 arcsec/century at 2-σ. This puts an upper bound on the vector unparticle couplings

$$2\pi(d_u - 1)(2d_u - 1)\frac{C'\left(d_u\right)\lambda^2 N_1 N_2}{Gm_1 m_2} \frac{1}{a^{2d_u-2}}\left(\frac{\text{century}}{T}\right) < 0.13 \text{ arcsec} \tag{39}$$

per century, where $T = 87.96$ days is the orbital time period of Mercury as stated before.

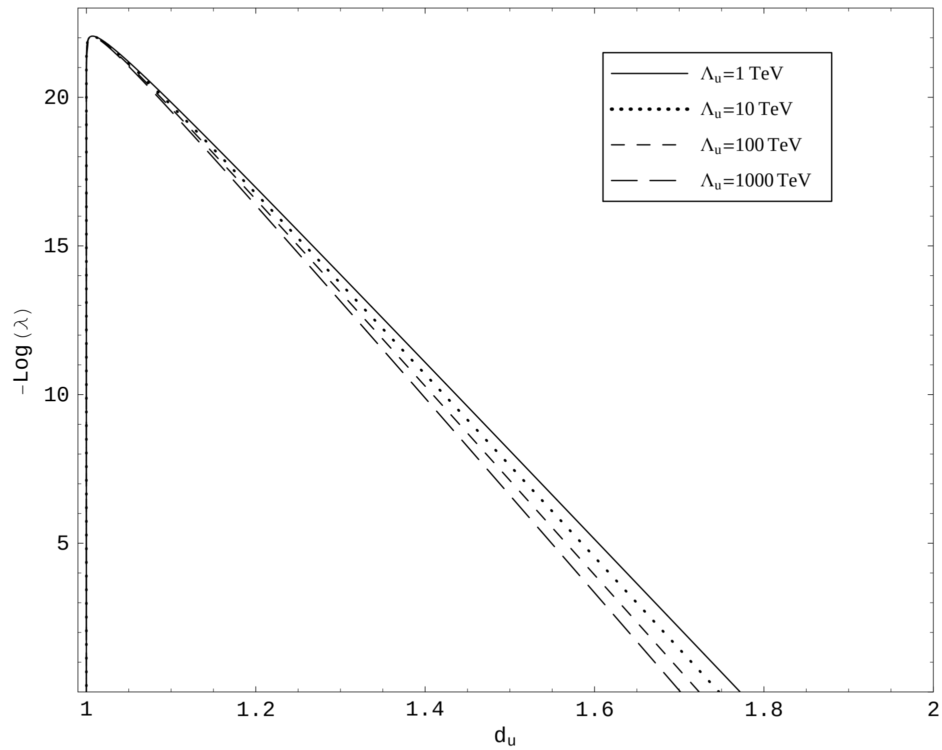

FIG. 2: Region above the curve represents the allowed values of $-\log(\lambda)$ and d_u from observations of Mercury orbit.

In Fig (2) we show $-\log(\lambda)$ vs. d_u plot taking $\delta\theta = 0.13$ arcsec/century. We have taken the values of Λ_u from 1 TeV to 1000 TeV. The areas above the curves represent the allowed values of λ and d_u at 2-σ experimental error for different Λ_u after accounting for the contribution to perihilion shift from general relativity.

CONCLUSIONS

There are several bounds on unparticle couplings to standard model particles from collider experiments [14] from the anomalous missing energy spectrum. There are also bounds on such couplings from the cooling rates of supernova and stars [10, 11, 12, 13]. If the conformal invariance of unparticles remains unbroken then these particles can give rise to extra long range forces [3, 4] which can be constrained from fifth force experiments [5]. In this paper we have considered unparticle gauge bosons of spin-1 and spin-2. The gauge symmetry ensures that the unparticles remain massless. The main characteristic feature of unparticle long range force which we apply in this paper is a deviation from the inverse square law

which leads to a perihelion shift in planetary orbits. The constraints from perihelion shift are more stringent than the constraints from the deviation from the inverse square law at the scale of solar system distances [7, 8]. However at milimeter scales there are stringent tests of deviations of Newton's Law as has been noted in [3, 4]. Compairing our bounds on vector and tensor unparticle couplings with that of [3] and [4] we find our bounds based on perihelion precession are more stringent when $d_u \lesssim 1.4$.

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